Evidence of a new narrow resonance decaying to $\chi_{c1}\gamma$ in $B \to \chi_{c1}\gamma K$

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E. Kato,[60] T. Kawasaki,[44] H. Kichimi,[13] C. Kiesling,[32] D. Y. Kim,[53] J. B. Kim,[26] J. H. Kim,[25] K. T. Kim,[26]
M. J. Kim,[27] Y. J. Kim,[25] K. Kinoshita,[5] J. Klucar,[22] B. R. Ko,[26] P. Kodyš,[4] S. Korpar,[31, 22] P. Križan,[29, 22]
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Y. Sato,[60] V. Savinov,[48] O. Schneider,[28] G. Schnell,[1, 14] C. Schwanda,[18] R. Seidl,[50] D. Semmler,[7] K. Senyo,[67]
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M. Uchida,[62] S. Uehara,[13] T. Uglov,[21, 35] Y. Unno,[11] P. Urquijo,[2] Y. Usov,[3] S. E. Vahsen,[12] C. Van Hulse,[1]
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We report measurements of $B \to \chi_{c1}\gamma K$ and $\chi_{c2}\gamma K$ decays using 772×10^6 $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. Evidence of a new resonance in the $\chi_{c1}\gamma$ final state is found with a statistical significance of 3.8 σ. This state has a mass of $3823.1 \pm 1.8(\mathrm{stat}) \pm 0.7(\mathrm{syst})$ MeV/c^2, a value that is consistent with theoretical expectations for the previously unseen 1^3D_2 $c\bar{c}$ meson. We find no other narrow resonance and set upper limits on the branching fractions of the $X(3872) \to \chi_{c1}\gamma$ and $\chi_{c2}\gamma$ decays.

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During the last decade, a number of new charmonium ($c\bar{c}$)-like states were observed, many of which are candidates for exotic states [1]. The first of these, the $X(3872)$, has been observed by six different experiments in the same final state [2–7]. A recent update from Belle [8] and LHCb [6] results in a world average mass at 3871.68 ± 0.17 MeV/c^2 [9] and a stringent upper bound on its width ($\Gamma < 1.2$ MeV) [8]. The proximity of its mass to the $D^{*0}\bar{D}^0$ threshold makes it a good candidate for a $D\bar{D}^*$ molecule [10]. Other, but alternative models have been proposed, such as a tetraquark [11] or a $c\bar{c}g$ hybrid meson [12].

Radiative decays can illuminate clearly the nature of hadrons. For example, the observation of $X(3872) \to J/\psi\gamma$ confirmed the C-even parity assignment for the $X(3872)$ [13, 14]. The similar decay mode $X(3872) \to \psi'\gamma$ could help to distinguish whether the $X(3872)$ is charmonium, a molecular state or a mixture of the two [10, 15, 16]. Belle reported no significant signal [14] in $X(3872) \to \psi'\gamma$, in disagreement with positive evidence from BaBar [13]. The $X(3872) \to \chi_{c1}\gamma$ and $\chi_{c2}\gamma$ decays are forbidden by C-parity conservation in electromag-

netic processes. However, if the $X(3872)$ is a tetraquark or a molecular state, it may have a C-odd partner, which could decay into $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ final states [17, 18].

In the charmonium family, the observation of a D-wave $c\bar{c}$ meson and its decay modes would test phenomenological models [19, 20]. The as-yet undiscovered 1^3D_2 $c\bar{c}$ (ψ_2) and 1^3D_3 $c\bar{c}$ (ψ_3) states are expected to have significant branching fractions to $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$, respectively [21, 22]. D-wave $c\bar{c}$ states and their properties were predicted long ago but remain unconfirmed [21, 22]. The E705 experiment reported an indication of a 1^3D_2 state in $\pi^\pm N \to J/\psi\pi^+\pi^- +$ anything, with a mass of 3836 ± 13 MeV/c^2 [23]; however, the statistical significance of this result was below the threshold for evidence.

In this letter, we report measurements of $B \to \chi_{c1}\gamma K$ and $B \to \chi_{c2}\gamma K$ decays, where the χ_{c1} and χ_{c2} decay to $J/\psi\gamma$ [24]. These results are obtained from a data sample of 772×10^6 $B\bar{B}$ events collected with the Belle detector [25] at the KEKB asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance [26]. The Belle detector is a large-solid-angle spectrometer, which includes a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L^0 mesons and identify muons (KLM).

The J/ψ meson is reconstructed via its decays to $\ell^+\ell^-$ ($\ell = e$ or μ). To reduce the radiative tail in the e^+e^- mode, the four-momenta of all photons within 50 mrad with respect to the original direction of the e^+ or e^- tracks are included in the invariant mass calculation, hereinafter denoted as $M_{e^+e^-(\gamma)}$. The reconstructed invariant mass of the J/ψ candidates is required to satisfy 2.95 GeV/c^2 < $M_{e^+e^-(\gamma)}$ < 3.13 GeV/c^2 or 3.03 GeV/c^2 < $M_{\mu^+\mu^-}$ < 3.13 GeV/c^2. For the selected J/ψ candidates, a vertex-constrained fit is applied and then a mass-constrained fit is performed in order to improve the momentum resolution. The χ_{c1} and χ_{c2} candidates are reconstructed by combining J/ψ candidates with a photon having energy (E_γ) larger than 200 MeV in the laboratory frame. Photons are reconstructed from the energy deposition in the ECL by requiring no matching with any extrapolated charged track. To reduce the background from $\pi^0 \to \gamma\gamma$, we use a likelihood function that distinguishes an isolated photon from π^0 decays using the photon pair invariant mass, photon laboratory energy and polar angle [27]. We reject both γ's in the pair if the π^0 likelihood probability is larger than 0.7. The reconstructed invariant mass of the χ_{c1} (χ_{c2}) is required to satisfy 3.467 GeV/c^2 < $M_{J/\psi\gamma}$ < 3.535 GeV/c^2 (3.535 GeV/c^2 < $M_{J/\psi\gamma}$ < 3.611 GeV/c^2). A mass-constrained fit is applied to the selected χ_{c1} and χ_{c2} candidates.

Charged kaons are identified by combining information from the CDC, TOF, and ACC systems. The kaon identification efficiency is 89% while the probability of misidentifying a pion as a kaon is 10%. K_S^0 mesons are reconstructed by combining two oppositely charged pions with the invariant mass $M_{\pi^+\pi^-}$ lying between 482 MeV/c^2 and 514 MeV/c^2. The selected candidates are required to satisfy the quality criteria described in Ref. [28].

To reconstruct B candidates, each χ_{cJ} [29] is combined with a kaon candidate and a photon having $E_\gamma >$ 100 MeV (and not used in the reconstruction of χ_{cJ}). If the invariant mass of any photon pair that includes this photon is found to be consistent with a π^0 (i.e., 117 MeV/c^2 < $M_{\gamma\gamma}$ < 153 MeV/c^2), this photon is rejected. Among the events containing at least one χ_{cJ} candidate, 9.0% have multiple χ_{cJ} candidates. In such cases, the γ forming the χ_{cJ} candidate with mass closest to the χ_{c1} or χ_{c2} masses [9] is not used as the additional photon. This treatment suppresses reflections from the χ_{cJ} daughter photons.

The B candidate is identified by two kinematic variables: the beam-constrained mass ($M_{\mathrm{bc}} \equiv \sqrt{E_{\mathrm{beam}}^{*2} - p_B^{*2}}$) and the energy difference ($\Delta E \equiv E_B^* - E_{\mathrm{beam}}^*$). Here, E_{beam}^* is the run-dependent beam energy, and E_B^* and p_B^* are the reconstructed energy and momentum, respectively, of the B meson candidates in the center-of-mass (CM) frame. Candidates within a ΔE window of $[-28, 30]$ MeV and with $M_{\mathrm{bc}} > 5.23$ GeV/c^2 are selected. Of these, 9.8% (6.4%) have multiple candidates in the $B^\pm \to \chi_{c1}\gamma K^\pm$ ($B^\pm \to \chi_{c2}\gamma K^\pm$) mode; we select the B candidate with ΔE closest to zero. In order to improve the resolution in $M_{\chi_{cJ}\gamma}$, we scale the energy of the γ so that ΔE is equal to zero. This corrects for incomplete energy measurement in the ECL. To suppress continuum background, events having a ratio R_2 of the second to zeroth Fox-Wolfram moments [30] above 0.5 are rejected.

The $M_{\chi_{c1}\gamma}$ and M_{bc} projections for the $B^\pm \to \chi_{c1}\gamma K^\pm$ signal candidates are shown in Fig. 1, where a $\psi' \to \chi_{c1}\gamma$ signal is evident. In addition, there is a significant narrow peak at 3823 MeV/c^2, denoted hereinafter as $X(3823)$. No signal of $X(3872) \to \chi_{c1}\gamma$ is seen. We extract the signal yield from a two-dimensional unbinned extended maximum likelihood (2D UML) fit to the variables $M_{\chi_{cJ}\gamma}$ and M_{bc}. The likelihood function is

$$\mathcal{L} = \frac{e^{-\sum_k n_k}}{N!} \prod_{i=1}^{N} \sum_k n_k P_k(m_{\mathrm{x}i}, M_{\mathrm{b}i}),$$

where k is the index for the signal and background contributions, n_k and P_k are the yield and probability density function (PDF), respectively, for the k-th component, $m_{\mathrm{x}i}$ and $M_{\mathrm{b}i}$ are the $M_{\chi_{cJ}\gamma}$ and M_{bc} values in the i-th event, respectively, and N is the total number of candidate events in the data.

The resolution in $M_{\chi_{cJ}\gamma}$ (M_{bc}) is parameterized by a

sum of two Gaussians (Gaussian and logarithmic Gaussian [31]). MC studies show that the resolutions in both $M_{\chi_{cJ}\gamma}$ and M_{bc} for a narrow resonance in the mass range 3.8 GeV/c^2 < $M_{\chi_{cJ}\gamma}$ < 4.0 GeV/c^2 are in good agreement with those for ψ'. The parameters of the resolution functions are determined from the MC simulation that is calibrated using the $B^{\pm} \to \psi'(\to \chi_{c1}\gamma)K^{\pm}$ signal. We take into account the ψ' natural width [9] by convolving the Breit-Wigner function and the resolution function; for the $X(3823)$ and $X(3872)$, zero natural widths are assumed. The two-dimensional PDF is a product of the one-dimensional distributions.

For $B^{\pm} \to \psi'(\to \chi_{c1}\gamma)K^{\pm}$ decay, the mean and width of the core Gaussian are floated and the remaining parameters are fixed according to MC. To fit the $B^{\pm} \to X(3823)(\to \chi_{c1}\gamma)K^{\pm}$ signal, we float the mean of the core Gaussian but constrain the detector resolution by using the ψ' signal results after taking into account the difference estimated from the signal MC study. For M_{bc}, the parameters are fixed to those found for the ψ', in accordance with expectations based on the MC simulation. We constrain the mass difference (from Ref. [9]) and the sigma difference (from MC simulations) between ψ' and $X(3872)$. To fit $B^0 \to \psi'(\to \chi_{c1}\gamma)K^0$, $B^0 \to X(3823)(\to \chi_{c1}\gamma)K^0$, $B \to \psi'(\to \chi_{c2}\gamma)K$, $B \to X(3823)(\to \chi_{c2}\gamma)K$ and $B \to X(3872)(\to \chi_{cJ}\gamma)K$, we fix all the parameters obtained from the signal MC study after correcting the PDF shapes by applying MC/data calibration factors.

To study background with a real J/ψ, we use large MC simulated $B \to J/\psi X$ samples corresponding to 100 times the integrated luminosity of the data. The non-J/ψ (non-χ_{cJ}) background is studied using $M_{\ell\ell}$ ($M_{J/\psi\gamma}$) sidebands in data. In the $B \to (\chi_{cJ}\gamma)K$ cases, the background with a broad peaking structure is mostly due to the $B \to \psi'(\nrightarrow \chi_{cJ}\gamma)K$, $B \to \chi_{cJ}K^*$, $B \to J/\psi K^*$ and $B \to \psi'K^*$ decay modes. $B \to \psi'(\nrightarrow \chi_{cJ}\gamma)K$ produces peaks in both distributions ($M_{\chi_{cJ}\gamma}$ and M_{bc}), while the other backgrounds are flat in $M_{\chi_{cJ}\gamma}$ but peaked in M_{bc}. We determine the PDFs from the large MC sample. The fractions of the PDF components are floated in the fit, except for $B \to \psi'(\nrightarrow \chi_{cJ}\gamma)K$, whose fraction is controlled by fixing its ratio to the $B \to \psi'(\to \chi_{cJ}\gamma)K$ signal yield. For the combinatorial background, a threshold function, $(M_{\chi_{cJ}\gamma})^2 \times \exp(a (M_{\chi_{cJ}\gamma} - M_{th}) + b (M_{\chi_{cJ}\gamma} - M_{th})^2 + c (M_{\chi_{cJ}\gamma} - M_{th})^3)$, where $M_{th} = 3.543$ GeV/c^2 (3.585 GeV/c^2) for $M_{\chi_{c1}\gamma}$ ($M_{\chi_{c2}\gamma}$), is used for $M_{\chi_{cJ}\gamma}$ and an ARGUS function [32] is used for M_{bc}. The value of M_{th} is estimated from a MC study; its variation, which affects the signal yield in the fits, is incorporated in the systematic errors. The ΔE data sidebands are used to verify the background PDFs. The fractions for the signal and the background components are floated in the fit.

The results of the fits are presented in Figs. 1-3 and in Table I. The significance is estimated using the value of $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ where $\mathcal{L}_{max}$ ($\mathcal{L}_0$) denotes the likelihood value when the yield is allowed to vary (is set
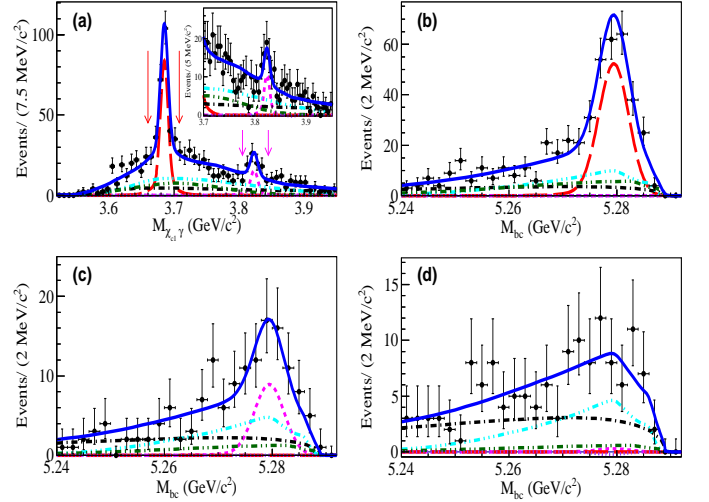

FIG. 1: 2D UML fit projection for $B^{\pm} \to (\chi_{c1}\gamma)K^{\pm}$ decays: (a) $M_{\chi_{c1}\gamma}$ distribution for M_{bc} > 5.27 GeV/c^2, (b) M_{bc} distribution for 3.660 GeV/c^2 < $M_{\chi_{c1}\gamma}$ < 3.708 GeV/c^2 (ψ' region, shown by red arrows), (c) M_{bc} distribution for 3.805 GeV/c^2 < $M_{\chi_{c1}\gamma}$ < 3.845 GeV/c^2 ($X(3823)$ region, shown by magenta arrows) and (d) M_{bc} distribution for 3.84 GeV/c^2 < $M_{\chi_{c1}\gamma}$ < 3.89 GeV/c^2 ($X(3872)$ region). The curves used in the fits are described in [33].

to zero). In the likelihood calculation, the χ^2 statistic uses the appropriate number of degrees of freedom (2 in case of $B^{\pm} \to X(3823)K^{\pm}$ and 1 for the other decay modes). The systematic uncertainty, which is described below, is included in the significance calculation [34]. We find a significant ψ' signal in all considered channels. We also obtain evidence for the $X(3823)$ in the channel $B^{\pm} \to \chi_{c1}\gamma K^{\pm}$ with a statistical significance of 3.8 standard deviations (σ). The $X(3872)$ signals are insignificant. We estimate the branching fractions according to the formula $\mathcal{B} = \frac{Y}{\epsilon \times \mathcal{B}_s \times N_{B\bar{B}}}$; here, Y is the yield, ϵ is the reconstruction efficiency, $\mathcal{B}_s$ is the secondary branching fractions taken from Ref. [9] and $N_{B\bar{B}}$ is the number of the $B\bar{B}$ mesons in the data sample. Equal production of neutral and charged B meson pairs in the $\Upsilon(4S)$ decay is assumed. Measured branching fractions for the ψ' are in agreement with the world average values for all the channels [9]. We set 90% confidence level (C.L.) upper limits (U.L.) on the insignificant channels using frequentist methods based on an ensemble of pseudo-experiments.

A correction for small differences in the signal detection efficiency between MC and data has been applied for the lepton and kaon identification requirements. Uncertainties in these corrections are included in the systematic error. The $\gamma\gamma \to \ell^+\ell^-$ and $D^{*+} \to D^0(K^-\pi^+)\pi^+$ samples are used to estimate the lepton identification correction and the kaon (pion) identification correction, respectively. To estimate the correction and residual systematic uncertainty for K_S^0 reconstruction, $D^{*+} \to D^0(\to$

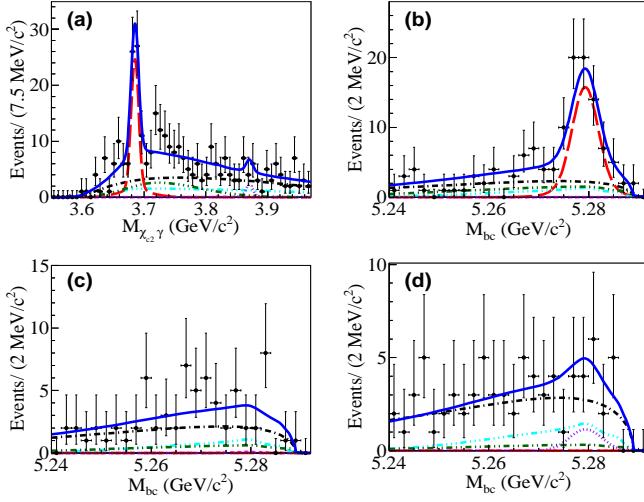FIG. 2: 2D UML fit projection for $B^{\pm} \to (\chi_{c2}\gamma)K^{\pm}$ decays: (a) $M_{\chi_{c2}\gamma}$ distribution for $M_{\rm bc} > 5.27$ GeV/c^2, (b) $M_{\rm bc}$ distribution for 3.660 GeV/$c^2 < M_{\chi_{c2}\gamma} < 3.708$ GeV/c^2 (ψ' region), (c) $M_{\rm bc}$ distribution for 3.805 GeV/$c^2 < M_{\chi_{c2}\gamma} < 3.845$ GeV/c^2 ($X(3823)$ region) and (d) $M_{\rm bc}$ distribution for 3.84 GeV/$c^2 < M_{\chi_{c2}\gamma} < 3.89$ GeV/c^2 ($X(3872)$ region). The curves used in the fits are described in [33].

$K_S^0 \pi^+ \pi^-)\pi^+$ samples are used. The errors on the PDF shapes are obtained by varying all fixed parameters by $\pm 1\sigma$ and taking the change in the yield as the systematic uncertainty. The uncertainties due to the secondary branching fractions are also taken into account. The uncertainties of the tracking efficiency and $N_{B\bar{B}}$ are estimated to be 0.35% per track and 1.4%, respectively. The uncertainty on the photon identification is estimated to be 2.0%/photon. The systematic uncertainty associated with the difference of the π^0 veto between data and MC is estimated to be 1.2% from a study of the $B^{\pm} \to \chi_{c1}(\to J/\psi\gamma)K^{\pm}$ sample.

We also perform a simultaneous fit to $B^{\pm} \to (\chi_{c1}\gamma)K^{\pm}$ and $B^0 \to (\chi_{c1}\gamma)K_S^0$, assuming that $\mathcal{B}(B^{\pm} \to X(3823)K^{\pm})/\mathcal{B}(B^0 \to X(3823)K^0) = \mathcal{B}(B^{\pm} \to \psi'K^{\pm})/\mathcal{B}(B^0 \to \psi'K^0)$. The ψ' peak position and $M_{\chi_{c1}\gamma}$ resolution are common for both charged and neutral B candidates. From this fit, we estimate the significance for $X(3823)$ to be 4.0 σ (including systematic uncertainties). We determine the mass of the signal peak relative to the well-measured ψ' mass :

$$M_{X(3823)} = M_{X(3823)}^{\rm meas} - M_{\psi'}^{\rm meas} + M_{\psi'}^{\rm PDG}$$
$$= 3823.1 \pm 1.8 \pm 0.7 \text{ MeV}.$$

Here, the first uncertainty is statistical and the second is systematic. Because of the mass-constrained fit to the $\chi_{c1}\gamma$ candidate, the systematic uncertainty of $M_{X(3823)}$ is dominated by the additional photon's energy scale. This photon energy scale uncertainty is estimated by the difference between the $\chi_{c1} \to J/\psi\gamma$ candidates' mass without any constraint and the χ_{c1} nominal mass [9], which
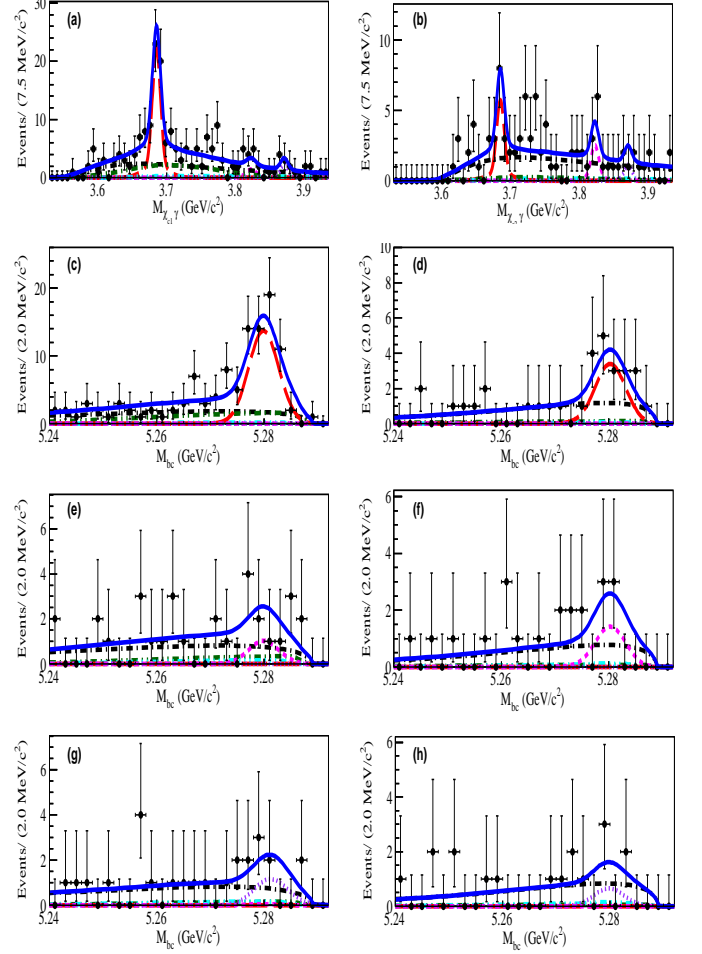

FIG. 3: 2D UML fit projection for $B^0 \to (\chi_{cJ}\gamma)K_S^0$ decays: (a) $M_{\chi_{c1}\gamma}$ distribution for $M_{\rm bc} > 5.27$ GeV/c^2, (b) $M_{\chi_{c2}\gamma}$ distribution for $M_{\rm bc} > 5.27$ GeV/c^2, (c) $M_{\rm bc}$ distribution for 3.660 GeV/$c^2 < M_{\chi_{c1}\gamma} < 3.708$ GeV/c^2 (ψ' region), (d) $M_{\rm bc}$ distribution for 3.660 GeV/$c^2 < M_{\chi_{c2}\gamma} < 3.708$ GeV/c^2 (ψ' region), (e) $M_{\rm bc}$ distribution for 3.805 GeV/$c^2 < M_{\chi_{c1}\gamma} < 3.845$ GeV/c^2 ($X(3823)$ region), (f) $M_{\rm bc}$ distribution for 3.805 GeV/$c^2 < M_{\chi_{c2}\gamma} < 3.845$ GeV/c^2 ($X(3823)$ region), (g) $M_{\rm bc}$ distribution for 3.84 GeV/$c^2 < M_{\chi_{c1}\gamma} < 3.89$ GeV/c^2 ($X(3872)$ region) and (h) $M_{\rm bc}$ distribution for 3.84 GeV/$c^2 < M_{\chi_{c2}\gamma} < 3.89$ GeV/c^2 ($X(3872)$ region). The curves used in the fits are described in [33].

results in 0.7 MeV as the $M_{X(3823)}$ systematic error. In order to estimate the width, we float this parameter and find no sensitivity with the available statistics: the width is 1.7 ± 5.5 MeV. Using pseudo-experiments generated with different width hypotheses for the $X(3823)$, the U.L. at 90% C.L. on its width is estimated to be 24 MeV.

The mass of the $X(3823)$ is near the potential model expectations for the 1^3D_J states' centroid mass: the Cornell [19] and the Buchmüller-Tye [20] potentials give 3810 MeV/c^2. Other models predict the mass of ψ_2 (the 1^3D_2 $c\bar{c}$ state, having $J^{PC} = 2^{--}$) to be 3815-3840 MeV/c^2 [35–37]. The $X(3823)$ mass agrees quite well
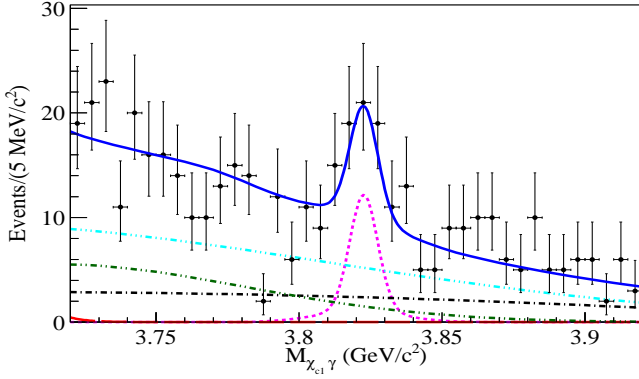
FIG. 4: 2D UML fit projection of $M_{\chi_{c1}\gamma}$ distribution for the simultaneous fit of $B^{\pm} \to (\chi_{c1}\gamma)K^{\pm}$ and $B^0 \to (\chi_{c1}\gamma)K^0_S$ decays for $M_{\mathrm{bc}} > 5.27$ GeV/c^2. The curves used in the fits are described in [33].

TABLE I: Summary of the results. Signal yield (Y) from the fit, significance ($\mathcal{S}$) with systematics included, corrected efficiency (ϵ) and measured $\mathcal{B}$. For $\mathcal{B}$, the first (second) error is statistical (systematic). Here, in the neutral B decay case, the $K^0_S \to \pi^+\pi^-$ branching fraction is included in the efficiency (ϵ) but the factor of 2 (for $K^0 \to K^0_S$ or K^0_L) is separately taken into account.

Decay	Yield (Y)	$\mathcal{S}(\sigma)$	$\epsilon(\%)$	Branching fraction
$B^{\pm} \to \psi'(\to \chi_{cJ}\gamma)K^{\pm}$				$\mathcal{B}(10^{-4})$
χ_{c1}	193.2 ± 19.2	14.8	8.6	$7.7 \pm 0.8 \pm 0.9$
χ_{c2}	59.1 ± 8.4	7.8	6.0	$6.3 \pm 0.9 \pm 0.6$
$B^0 \to \psi'(\to \chi_{cJ}\gamma)K^0$				
χ_{c1}	50.3 ± 7.3	7.2	5.1	$6.8 \pm 1.0 \pm 0.7$
χ_{c2}	12.9 ± 4.4	2.9	3.5	$4.7 \pm 1.6 \pm 0.8$
$B^{\pm} \to X(3823)(\to \chi_{cJ}\gamma)K^{\pm}$				$\mathcal{B}(10^{-6})$
χ_{c1}	33.2 ± 9.7	3.8	10.9	$9.7 \pm 2.8 \pm 1.1$
χ_{c2}	0.3 ± 3.9	0.1	8.8	< 3.6
$B^0 \to X(3823)(\to \chi_{cJ}\gamma)K^0$				
χ_{c1}	3.9 ± 3.4	1.2	6.0	< 9.9
χ_{c2}	5.3 ± 2.9	2.4	5.0	< 22.8
$B^{\pm} \to X(3872)(\to \chi_{cJ}\gamma)K^{\pm}$				
χ_{c1}	-0.9 ± 5.1		11.1	< 1.9
χ_{c2}	4.7 ± 4.4	1.3	9.3	< 6.7
$B^0 \to X(3872)(\to \chi_{cJ}\gamma)K^0$				
χ_{c1}	4.6 ± 3.0	1.6	6.2	< 9.6
χ_{c2}	2.3 ± 2.2	1.1	5.2	< 12.2

with these models. In addition, since no peak has been seen around $X(3823)$ in the $D\bar{D}$ final state [38], one expects that ψ_2 does not decay to $D\bar{D}$ [36]. The ratio $R_B = \frac{\mathcal{B}(X(3823) \to \chi_{c2}\gamma)}{\mathcal{B}(X(3823) \to \chi_{c1}\gamma)} < 0.41$ (at 90% C.L.) is consistent with the expectation ($R_B \sim 0.2$) for ψ_2 [39, 40]. The limited data preclude an analysis of the decay product angular distribution to determine the J^{PC} assignment of the $X(3823)$. The product of branching fractions for the

$X(3823)$ is approximately two orders of magnitude lower than for the ψ', as shown in Table I; it is consistent with the interpretation of the $X(3823)$ as $\psi_2(1^3D_2)$, whose production rate is suppressed by the factorization [41] in the two-body B meson decays.

In summary, we obtain the first evidence of a narrow state, $X(3823)$, that decays to $\chi_{c1}\gamma$ with a mass of $3823.1 \pm 1.8(\mathrm{stat}) \pm 0.7(\mathrm{syst})$ MeV/c^2 and a significance of 3.8 σ, including systematic uncertainties. We measure the branching fraction product $\mathcal{B}(B^{\pm} \to X(3823)K^{\pm})\mathcal{B}(X(3823) \to \chi_{c1}\gamma) = (9.7 \pm 2.8 \pm 1.1) \times 10^{-6}$. No evidence is found for $X(3823) \to \chi_{c2}\gamma$ and we set an U.L. on its branching fraction product $\mathcal{B}$ as well as the ratio $R_B \equiv \frac{\mathcal{B}(X(3823) \to \chi_{c2}\gamma)}{\mathcal{B}(X(3823) \to \chi_{c1}\gamma)} < 0.41$ at 90% C.L. The properties of the $X(3823)$ are consistent with those expected for the ψ_2 (1^3D_2 $c\bar{c}$) state. We also determine the U.L. on the product of the branching fractions, $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm})\mathcal{B}(X(3872) \to \chi_{c1}\gamma) < 1.9 \times 10^{-6}$ at 90% C.L.; this is less than one quarter of the corresponding value in $X(3872) \to J/\psi\pi^+\pi^-$ [9]. In addition, we obtain constraints for all of the $\chi_{cJ}\gamma K$ final states in neutral and charged B decays. Our results show that the $X(3872)$'s C-odd partner production in the two-body B decays or its decay into $\chi_{cJ}\gamma$ are found to be considerably suppressed.

[1] N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011).
[2] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[3] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **93**, 072001 (2004).
[4] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **93**, 162002 (2004).
[5] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **71**, 071103 (2005).
[6] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **72**, 1972 (2012).
[7] V. Chiochia *et al.* (CMS Collaboration), arXiv:hep-

ex/1201.6677.

[8] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. D **84**, 052004 (2011).

[9] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012).

[10] E.S. Swanson, Phys. Lett. B **598**, 197 (2004); E.S. Swanson, Phys. Rept. **429**, 243 (2006).

[11] L. Maiani *et al.*, Phys. Rev. D **71**, 014028 (2005).

[12] B.A. Li, Phys. Lett. B **605**, 306 (2005).

[13] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **102**, 132001 (2009).

[14] V. Bhardwaj *et al.* (Belle Collaboration), Phys. Rev. Lett. **107**, 091803 (2011).

[15] T. Mehen and R. Springer, Phys. Rev. D **83**, 094009 (2011).

[16] T.H. Wang and G.L. Wang, Phys. Lett. B **697**, 233 (2011).

[17] K. Terasaki, Prog. Theor. Phys. **127**, 577 (2012).

[18] J. Nieves and M. P. Valderrama, Phys. Rev. D **86**, 056004 (2012).

[19] E. Eichten *et al.*, Phys. Rev. D **17**, 3090 (1978); E. Eichten *et al.*, Phys. Rev. D **21**, 203 (1980).

[20] W. Buchmüller and S.-H.H. Tye, Phys. Rev. D **24**, 132 (1981).

[21] E.J. Eichten, K. Lane and C. Quigg, Phys. Rev. Lett. **89**, 162002 (2002).

[22] P. Cho and M.B. Wise, Phys. Rev. D **51**, 3352 (1995).

[23] L. Antoniazzi *et al.* (E705 Collaboration), Phys. Rev. D **50**, 4258 (1994). Note that no hint of $\psi(3836)$ is seen in the $J/\psi\pi^+\pi^-$ studies focused on $X(3872)$ [2–7].

[24] Charge-conjugate and neutral modes are included throughout the paper unless stated otherwise.

[25] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002); also see detector section in J. Brodzicka *et al.*, Prog. Theor. Exp. Phys. (2012) 04D001.

[26] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this Volume; T. Abe *et al.*, Prog. Theor. Exp. Phys. (2013) 03A001 and following articles up to 03A011.

[27] P. Koppenburg *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 061803 (2004).

[28] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. D **72**, 012004 (2005).

[29] Hereinafter, χ_{cJ} refers to either χ_{c1} or χ_{c2}, depending on which is reconstructed.

[30] G. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[31] The logarithmic Gaussian is parameterized as:
$f(x) = \frac{N_0}{\sqrt{2\pi}\sigma_0(\epsilon-x)} \exp-\frac{(\ln(\frac{\epsilon-x}{\epsilon-x_p}))^2}{2\sigma_0^2}$, where $\epsilon = \frac{\sigma}{a} + x_p$ and $\sigma_0 = \frac{\ln(a\sqrt{2\ln 2}+\sqrt{1+2a^2\ln 2})}{\sqrt{2\ln 2}}$. Here, N_0 is the normalization, σ is the standard deviation, x_p is the mean and a is the asymmetry.

[32] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990).

[33] The curves show the signal [red large-dashed for ψ', magenta dashed for $X(3823)$ and violet dotted for $X(3872)$] and the background component [black dotted-dashed for combinatorial, dark green two dotted-dashed for $B \to \psi'(\nrightarrow \chi_{cJ}\gamma)K$ and cyan three dotted-dashed for peaking component] as well as the overall fit [blue solid]. $B \to \psi'(\nrightarrow \chi_{cJ}\gamma)K$ is specific to the decay mode under study.

[34] R.D. Cousins and V.L. Highland, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 331 (1992).

[35] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985).

[36] E. Eichten, K. Lane and C. Quigg, Phys. Rev. D **69**, 094019 (2004).

[37] M. Blank and A. Krassnigg, Phys. Rev. D **84**, 096014 (2011).

[38] P. Pakhlov *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 202001 (2008).

[39] P. Ko, J. Lee and H.S. Song, Phys. Lett. B **395**, 107 (1997).

[40] C.-F. Qiao, F. Yuan and K.-T. Chao, Phys. Rev. D **55**, 4001 (1997).

[41] M. Suzuki, Phys. Rev. D **66**, 037503 (2002); P. Colangelo, F. De Fazio and T.N. Pham, Phys. Lett. B **542**, 71 (2002).